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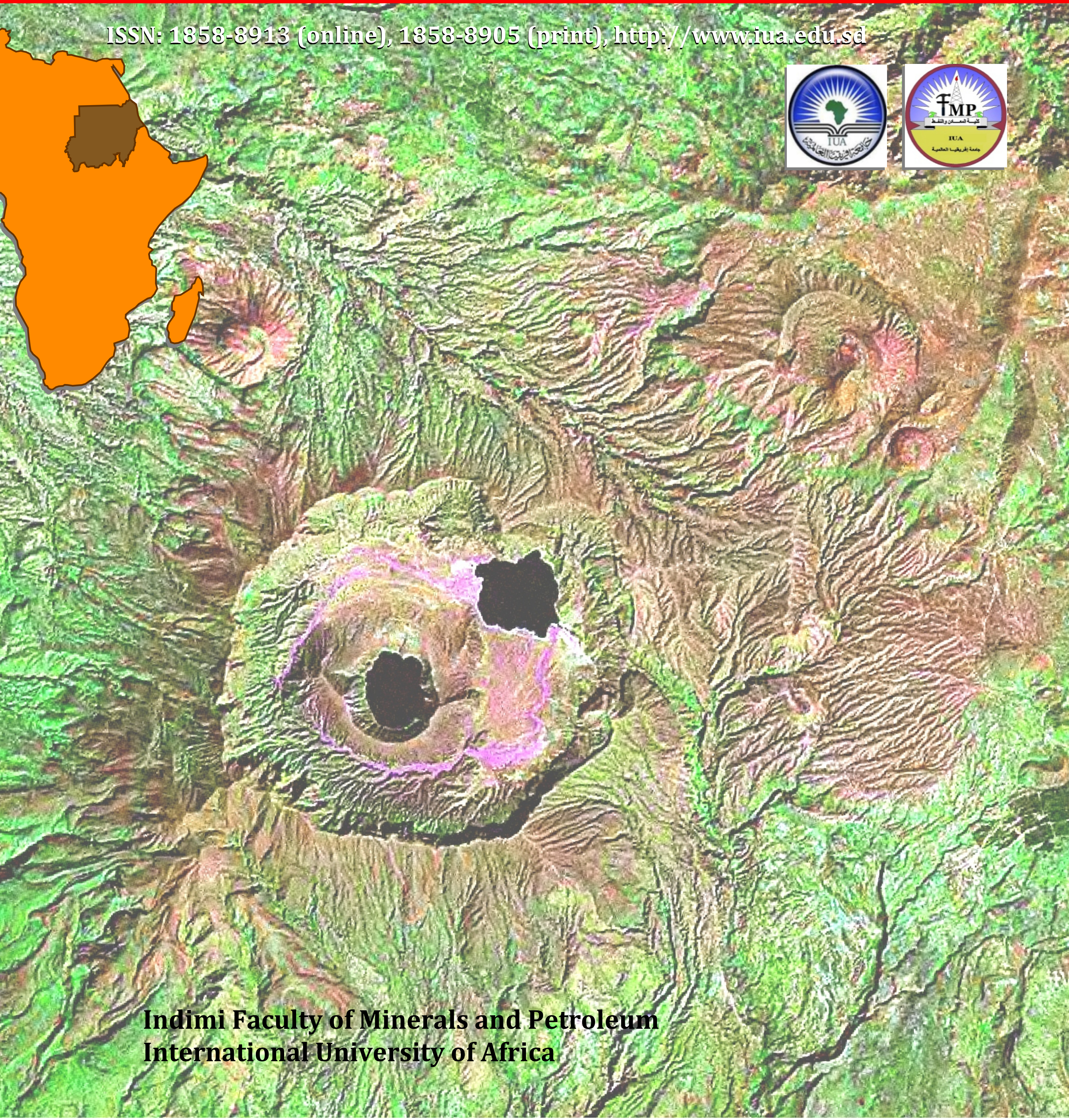

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Groundwater Flow Assessment Based on Numerical Simulation at Omdurman Area, Khartoum State, Sudan

Adil Balla Elkrail and Mohammed Adlan

Faculty of Petroleum and Minerals, Al Neelain University, Khartoum -Sudan.
P. O. Box: 12702, Postal Code. 11121, Fax : 00249-183-771154,
E-mail: adilmagboul321@yahoo.com

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Abstract

Visual MODFLOW computer code was selected to simulate head distribution, calculate the zone budgets of the area, evaluate the effect of external stresses on the groundwater head and to demonstrate how the groundwater model can be used as a comparative technique in order to optimize utilization of the groundwater resource. Conceptual model of the study area, aquifer parameters, boundary and initial conditions were used to simulate the flow model. Trial-and-error technique was used to calibrate the model. The most important criteria that used to check the calibrated model were Root Mean Squired Error (RMS), Absolute Residual Mean (ARM), Normalized (RMS%) and mass balance. Observation wells elaborate the reasonable match between the observed and calculated heads through the entire simulation period. The maps of the simulated heads, elaborated acceptable model calibration compared to observed heads map. The transient simulation for four stress periods within two years showed that the continuation of pumping will cause insignificant changes in head distribution and components of groundwater budget. Hence the area under consideration may represent high permeable and productive zone and strongly recommended for further groundwater development projects.

Key Words: Aquifers, model simulation, groundwater, calibrations, trail-and- error, water balance

1. Introduction

Groundwater model is regarded as the best tool to conceptualize the hydrogeological situation in the groundwater basins (Anderson and Woessner, 1992) and to predict the potential environment and socioeconomic impacts of the groundwater abstractions.

Recently there is an increasing concern on the groundwater quantity and quality to meet the drastic increase in population, economic, industrial, and agricultural developments in the study area. The urban development with rapid economic and population growth have direct impact on the spatial distribution of groundwater discharge (Zektser, 2000) Groundwater models are the most effective way of quantifying groundwater potentiality, through simulation of hydraulic heads, inflow rate, outflow rate and mass balance in aquifers, based on existing or anticipated parameters and assessing the effects of various stresses on the aquifer system (Domenico and Schwartz, 1998). Moreover, mathematical modeling of groundwater contamination with varying velocity field, recently, were resent (Das et al. 2017 and Yadav. and Kumar 2018). Eventually, these tools have significantly expanded the ability to understand and manage water resources (Osman and Bruen, 2002).

The main objectives of this paper are to construct a numerical groundwater flow model based on the existing hydrogeologic conceptual model to suite the numerical model setup for assessing the groundwater potentiality, determine the effects of stresses on the aquifer, simulate the hydraulic head distribution in model domain, determine the reliability of the numeric model to improve the understanding of the complex hydrogeological situation of the basin, and to calculate the hydrologic budget components of the model domain, using visual MODFLOW code. The results of the model calculations can be used to redefine and optimize the exploration drilling and the field survey.

2. Geomorphology, Geology and Hydrogeology

The model area is situated in western part of White Nile and River Nile(Omdurman area), between latitudes 15.24º - 15.51º N and longitudes 32.26º - 32.45º E in a relatively low undulated peneplain (380-450 m a.s.l, Fig. 1). It is characterized by semi-desert climate of very hot and dry summer (March-July), short rainy season (July to September) and cold dry winter. The mean annual rainfall is 167mm.

The area is covered by Cretaceous-sedimentary aquifers. Ravines and valleys are commonly distributed. Moreover seif types of sand dunes characterize the western part of the study area. They are aligned in more or less N-S direction and extended up to 300 Km with a width of about 7 km (Saeed, 1976).

The geologic setting is composed of the Precambrian-Cambrian Basement complex, Mesozoic sedimentary rocks and Quaternary formation which comprises unconsolidated sand, gravel, cobble, pebble, silt, and clay and paddy soil of alluvial deposits. These deposits embrace the main aquifers system. Basement complex, underlain the sedimentary formations forming its bottom limit at variable depths, which sometimes reaches more than 500m.

The aquifer system is mainly composed of two aquifers separated with aquitards and aquicludes developed in the Cretaceous Sedimentary formation and Quaternary deposits. The upper aquifer was assumed to be confined, with thickness varies from 18 to 97 m and increases southward up to 120 m. The lower aquifer is mostly confined and its thickness varies between 150- 500m (Kohnke, et al. 1993). The upper surface of the lower aquifer (second layer) varies from 219 to 297m,a.s.l. The depth to the piezometric surface ranges from a few meters near the Nile to more than 140 m at the northwestern part of the study area.

The River Nile, White Nile, seasonal wadies and direct rainfall are almost the main source of groundwater recharge (Elkrail et al. 2003).

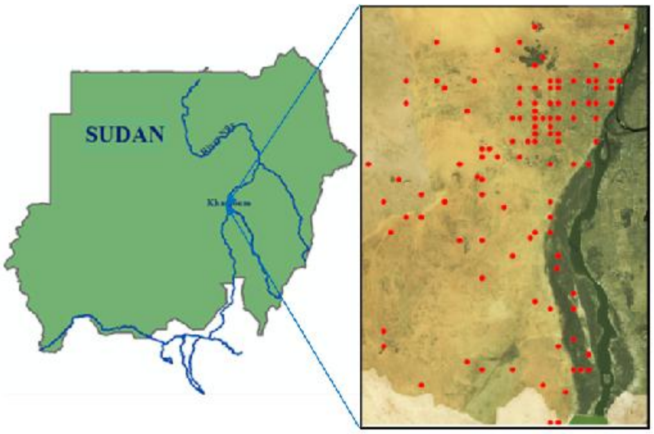

Fig. 1. Location and wells distribution map

3. Model Construction

The three-dimensions, block-centered, finite difference and transient groundwater flow model was constructed. The visual MODFLOW computer code was selected to improve the understanding of the complex hydrogeological situation of the model area. The initial grid networks of 80 rows, 90 columns and 4 layers and 28800 cells were used to cover the model area. The visual MODFLOW computer code is based on partial differential equation of flow and solute transport. The Governing Equations which describe the three dimensional movement of groundwater flow of constant density through the porous media is (Freeze and Cherry, 1979):

$$\frac{\partial}{\partial x}(K_x \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(K_y \frac{\partial h}{\partial y}) + \frac{\partial}{\partial z}(K_z \frac{\partial h}{\partial z}) - w = S_s \frac{\partial h}{\partial t} \text{...(1)}$$

where: K_x, K_y, K_z: are values of hydraulic conductivity along the x, y and z coordinate axes (L/t); h: is the potentiometric head (L); w: is the volumetric flux per unit volume and represents sources and/or sinks of water per unit time (t-1); S_s: is the specific storage of the porous material (L-1); and t: is time (t). The first part of this problem was run to get a steady state solution that takes the form:

$$\frac{\partial}{\partial x}(K_x \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(K_y \frac{\partial h}{\partial y}) + \frac{\partial}{\partial z}(K_z \frac{\partial h}{\partial z}) - w = 0.0 \text{...(2)}$$

The above partial differential equations describe the three-dimensional groundwater flow of constant density through porous medium can be solved for steady and transient flow conditions.

The model was simulated for a time period of two years (2013-2015), divided into 4 simulation periods each of six months length (181 days). Based on the output obtained from trail runs, the value of 10 and 1.4 were chosen for the time step and time-step multiplier respectively for the production runs. Horizontal hydraulic conductivity of the aquifers in the study area varies from 1.27 to 4.49 m/d throughout the model area according to Thies's and Jacob's analytical methods (Kruseman and De Ridder 1990). The vertical hydraulic conductivity (K_v) is considered as ten orders lower than the horizontal hydraulic conductivity. A uniform storage coefficient of 0.00383 was used for both aquifers for model simulation. The specific yield varies spatially from 0.15 to 0.23 in the model area. The effective porosity varies from 0.19 to 0.21 whereas; total porosity varies from 0.28 to 0.35. The first values of the abovementioned hydraulic properties were assigned to the upper aquifer, whereas; the second values were assigned to the lower aquifer respectively. The measured heads in sixteen observation wells at the year 2013 were used as initial head distribution for the model simulation. The bottom of the aquifer was considered as No-flow boundary. The eastern side of the model area was assigned as river boundary and the top of the aquifer as the variable head boundary, where flow may enter the model domain as a recharge from the rainfall and flooding monsoons. The southern side, the western side, and northern side of the model domain were assigned as General Head Boundary (GHB).

4. Model Calibration

Model calibration is a process of finding a set of boundary conditions, stresses, and hydrogeologic parameters, which produce the result that most closely matches field measurements of hydraulic heads and flows (Fritch, et al. 2000, Starn, et al., 2013). A prior calibration targets and criteria have been adopted based on the discrepancies between the field observed and the simulated groundwater heads at sixteen observation wells. During earlier stages of model calibration, an adjustment of the general head boundary, river stage, riverbed conductance, pumping rates, and recharge was performed to minimize the discrepancy between the observed and simulated heads. The aquifer hydraulic conductivity, storage coefficient and specific yield considered to be constant in each zone for the entire simulation period. The main calibration targets are heads and mass balances. Calibration was performed by adjusting the hydrologic parameters until the model approximated field-measured values of head, fluxes and pumping rates using the trail-and error procedure. Hundreds of model runs were performed to achieve a calibration. A regression plot of observed against simulated heads is one of the ways for reflecting the calibration fit (Fig. 2)

5. Model Results

The calibration of the three dimensional finite difference flow model of the study area was performed using the Root Mean Squired Error (RMS), Absolute Residual Mean (ARM), Normalized (RMS%) and mass balance percent discrepancy as indicative criteria. However model calibration revealed more acceptable with RMS of 0.881m, ARM of 0.663m and RMS% of 1.591% (Fig. 2) and mass balance percent discrepancy of 0.01%

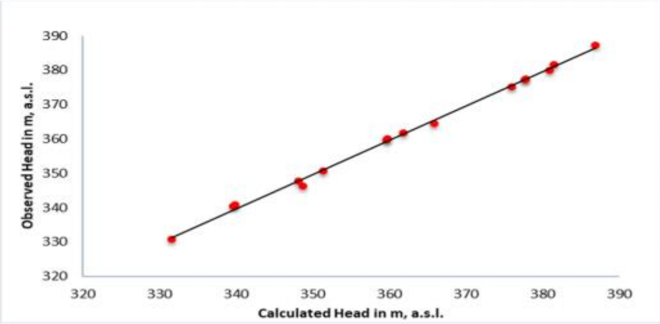

Fig. 2. Observed versus calculated head

The contour maps of the simulated heads were drawn using visual MODFLOW post-processing tool. Generally, water heads decline from the eastern boundary towards the west, confirming the expected groundwater recharge from the White Nile and River Nile (Fig. 3 & Fig. 4). An exceptional cone of depressions at the west and south part of the model domain are considered to be due to localized heavy pumping. The wide space contour lines (gentle hydraulic gradient) reflect the low effect of excessive groundwater abstraction for relatively long duration. Moreover, the contour lines shape and spacing were reflecting insignificant changes of pattern proportional to the groundwater abstraction with respect to the time (compare Fig.3 & Fig.4). Accordingly, the area under consideration may represent a productive target and high permeability zone. Finally the piezometric surface maps obtained from model simulation are more or less similar to that obtained from field head measurements (compare Figs. 3 & 4 with Fig. 5). Accordingly, acceptable model calibration was obtained and the model can be used for future prediction.

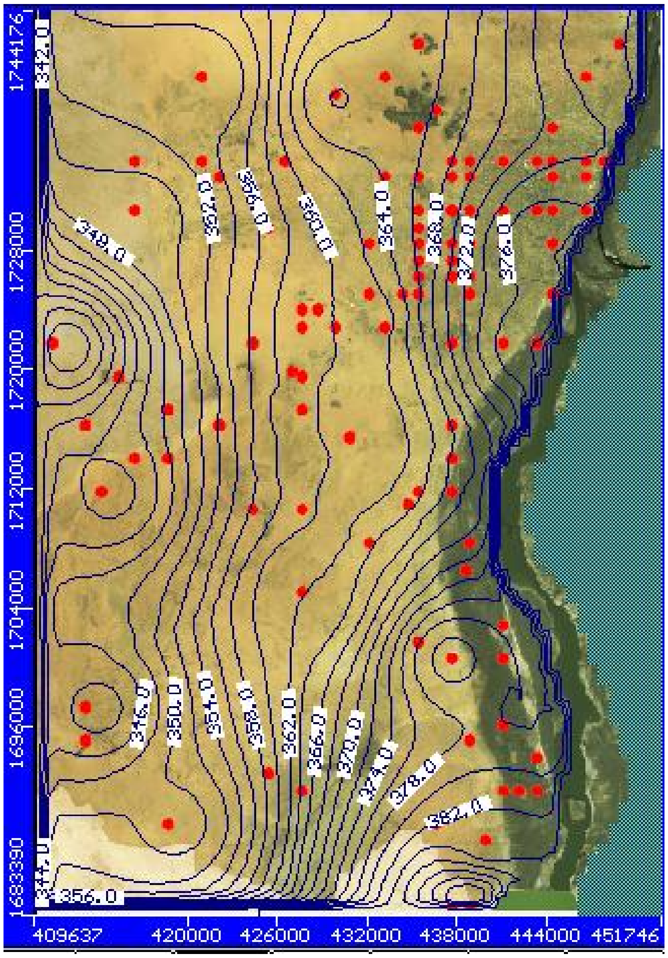

Fig. 3. Simulated piezometric surface at the fist stress period (181 days)

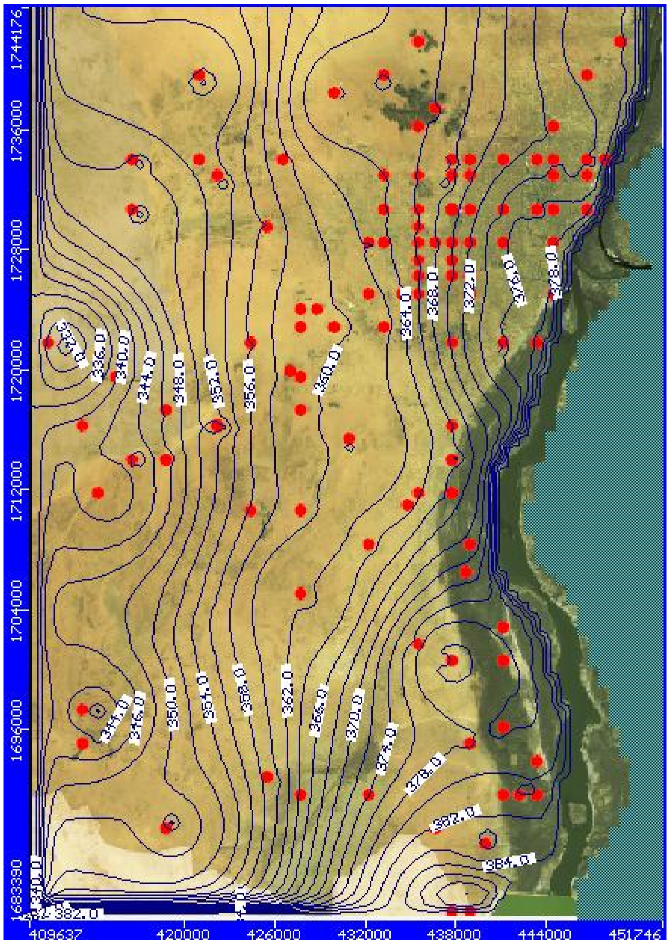

Fig. 4. Simulated piezometric surface at the last stress period (730 days)

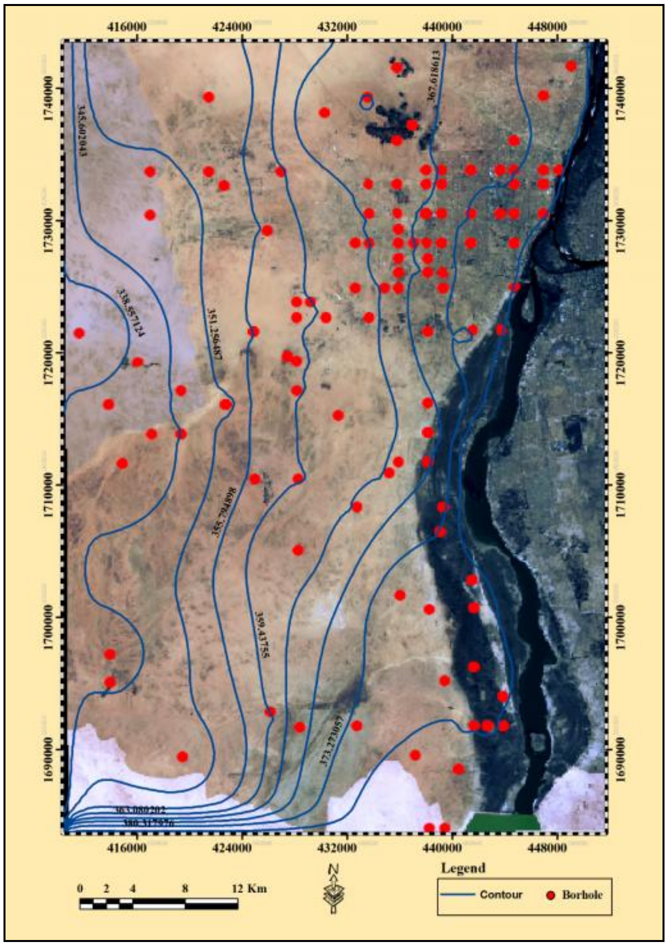

Fig. 5. Field measured piezometric surface map

6. Groundwater Budget

The groundwater budget was prepared to estimate the amount of groundwater inflow, out flow and changing in storage. Groundwater budget was calculated for the whole model area. The main calculated budget components include storage, pumpage, recharge, general head boundaries (GHB), river leakage and evapotranspiration (ET). The zone budget was calculated for the first, second, third and fourth stress periods respectively (Table 1). The volume rates of time step of water in million cubic meter per day (mcm/d) was calculated for each component of the hydrologic budget (table 1). Groundwater pumping volume in the entire area represents **20%** of the average outflow from the aquifer (table1). The subsurface flow through GHB to the aquifer represents **25.3%** from the average inflow, whereas subsurface flow out of the aquifer zone represents **19.8%.** The recharge water volume is significant and representing **14.5%** of the total inflow.

Table (1). Mass balance volume rates of time step for the model area

Time (Days)	**In Flow (mcm)**					**Out Flow (mcm)**						**Total Discrepancy (mcm)**
	storage	**River leakage**	**Recharge**	**GHB**	**Total**	**Storage**	**Well Discharge**	**River leakage**	**GHB**	**ET**	**Total**	
181	0.626	0.522	0.190	0.458	1.796	1.159	0.365	0.027	0.365	0.056	1.796	-8E-05
365	0.479	0.281	0.190	0.321	1.272	0.709	0.277	0.019	0.277	0.076	1.272	-6.7E-05
546	0.416	0.237	0.190	0.283	1.126	0.599	0.243	0.018	0.243	0.076	1.126	-7.2E-05
730	0.372	0.208	0.190	0.258	1.028	0.525	0.220	0.017	0.220	0.076	1.028	-7.2E-05
Average	0.473	0.312	0.190	0.330	1.306	0.748	0.276	0.020	0.276	0.071	1.306	-7.3E-05

It is obviously seen that all the mass balance components were decreasing continuously with time from the first stress period to last one (Table 1 & Fig.6). Evapotranspiration in the model domain is insignificant (5.1% from average outflow**)** due to relatively deep grounwater level with respect to extinction depth. The river leakage into the aquifer (23.9% from average inflow) represents an important recharge parameter relative to minimal river leakage out (1.5% from average outflow) of the aquifer and both are decreasing with time. The low deficit computed mass balance between outflows and inflows cannot create a significant drawdown of the potentiometric level (Table 1, Fig.3 & Fig. 4).

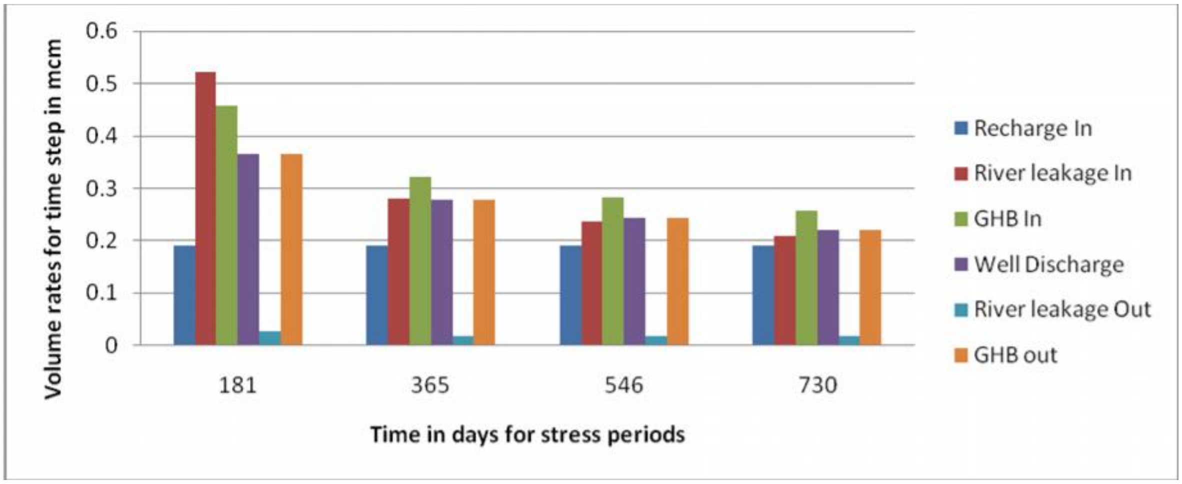

Fig. 6. Graphical representation of mass balance components in the model area

7. Conclusions

The aquifer system is mainly composed of two aquifers separated with aquitards and aquicludes developed in the Cretaceous Sedimentary formation and Quaternary deposits. The three-dimensions, block-centered, finite difference and transient groundwater flow model was constructed. The visual MODFLOW computer code was selected to improve the understanding of the complex hydrogeological situation of the model area. The initial grid networks of 80 rows, 90 columns and 4 layers and 28800 cells were used to cover the model area. The model was simulated for a time period of two years (2013-2015), divided into 4 simulation periods each of six months (length 181 days). The main calibration targets are heads and mass balances. The calibration was performed using the Root Mean Squired Error (RMS), Absolute Residual Mean (ARM), Normalized (RMS%) and mass balance percent discrepancy as indicative criteria. Model calibration revealed more acceptable results with RMS of 0.881m, ARM of 0.663m, RMS% of 1.591% and mass balance percent discrepancy of 0.01%. Generally, water heads decline from the eastern boundary towards the west, confirming the expected groundwater recharge from the White Nile and River Nile. The contour lines shape and spacing were reflecting insignificant changes of pattern proportional to the groundwater abstraction with respect to the time. The piezometric surface maps obtained from model simulation are more or less similar to that obtained from field head measurements. It is obviously seen that all the mass balance components were decreasing continuously with time from the first stress period to last one . The low deficit computed between outflows and inflows cannot create a significant drawdown of the potentiometric level. As the results,the area under consideration may represent a productive target and high permeable zone and accept more water developments. Finally, acceptable model calibration was obtained and the model can be used for future prediction.

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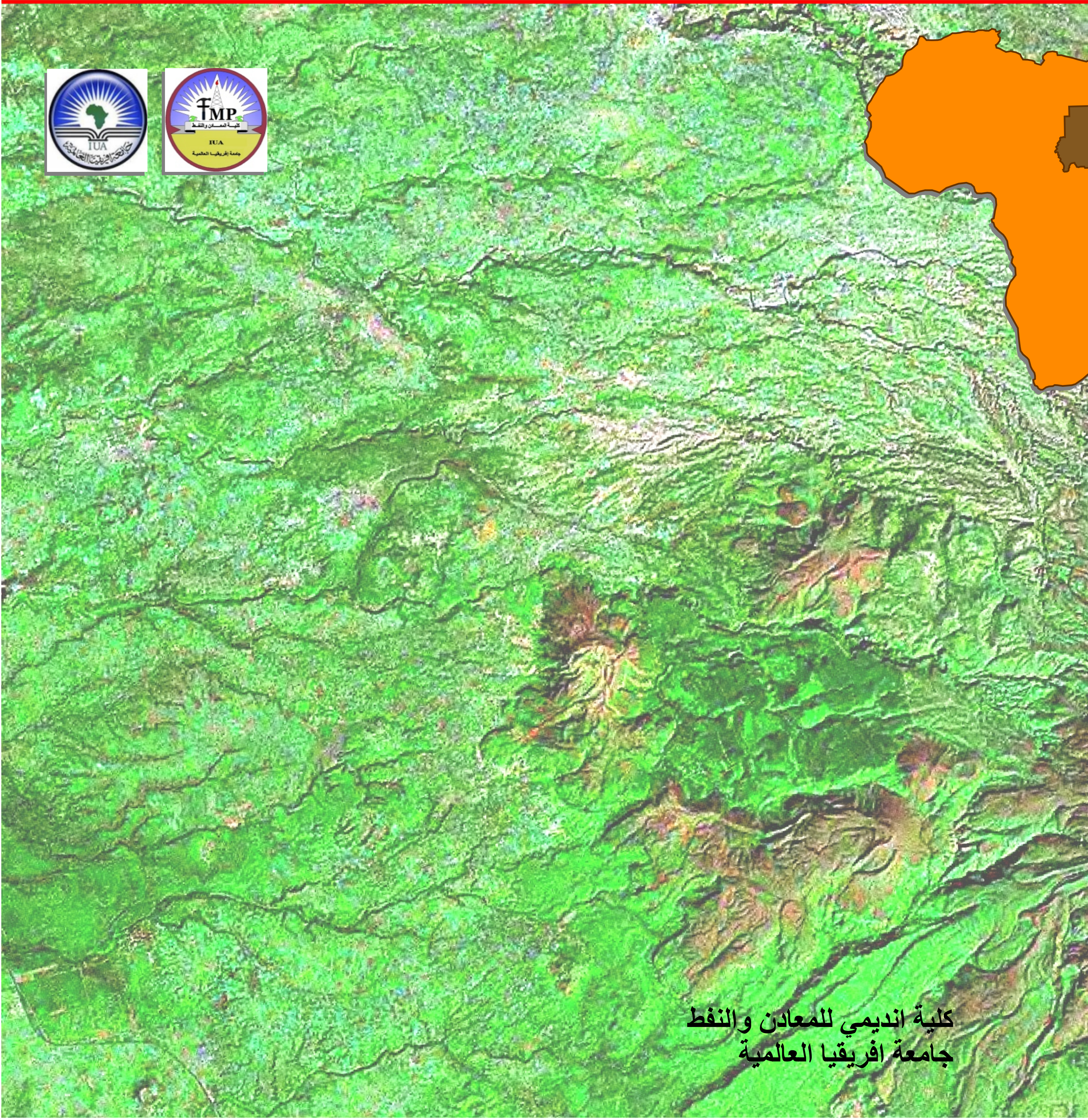

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